Energy Cost and Efficiency of a Demanding Combined Manual Materials-Handling Task

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Energy cost and crew performance were studied during a 45-hour continuous field-artillery loading exercise using a howitzer simulator. An interrupted peak $\dot{V}O_2$ test, conducted in the simulator, was used to develop individual equations to predict energy cost from heart rate. Nine experienced crew members went through six 1.5-hour loading cycles. Mission time (the time elapsed from the order to fire until task completion) was recorded and summed over cycles. Measures made at the end of each cycle included profile of mood state (POMS), rating of perceived exertion (RPE); rating of pain, soreness, and discomfort (RPSD), and isometric hand-grip strength. Results showed a significant decrease ($p < 0.01$) in energy cost (8.0–6.2 kcal·min^{-1}) and mission time (28.1–24.5 min) from Cycle 1 to Cycle 6. The POMS revealed an increase in fatigue and tension and a decrease in vigor ($p < 0.01$). RPE increased ($p < 0.05$) over time as did RPSD reported for the shoulders, arms, and hands ($p < 0.05$). Isometric hand-grip strength decreased 8.6% ($p < 0.01$) from Cycle 1 to Cycle 6. The efficiency of howitzer loading performance increased; however, the changes in RPE, POMS, hand grip, and RPSD suggest that longer duration exercises may result in performance decrements. These data indicate that simulators can improve the performance of this task.

Keywords: Sustained work; Energy cost; Efficiency; Simulator; Exertion; Muscle contraction

Operation of a field-artillery gun is one of the most physically demanding jobs in the military. The self-propelled 155-mm howitzer is a tracked vehicle with a rotating turret that fires 45-kg explosive projectiles out of an extended barrel. Crew members move the projectiles several times before they load them onto a waist-high loading tray to be hydraulically pushed into the barrel rifling. Operation of this heavy equipment in a realistic environment often involves long periods of intense loading exercise. Because of the costs and safety risks involved (Knapik, Patton, Ginsberg, et al.,

1987; Patton, Vogel, Damokosh, et al., 1987), there have been very few physiological studies of people operating field-artillery equipment; the few studies conducted have not measured energy cost. A field-artillery model was developed in the laboratory, but the model did not involve the same movements or equipment as those of an actual field-artillery gun (Sharp, Harman, Boutilier, et al., 1993).

A recently developed field-artillery simulator duplicates the movements involved in loading and firing a 155-mm howitzer gun. In the experiment reported in this article, the simulator was used during a 45-hour continuous-operations exercise to determine 1) the energy cost of loading and firing the howitzer simulator and 2) the effects of the 45-hour exercise on hand-grip strength, ratings of perceived exertion, and ratings of pain, soreness, and discomfort.

METHODS

Subjects

Nine experienced male field-artillery crewmen volunteered to participate in this study. All were briefed on the purposes and risks of the study; they then read and signed an informed consent statement. Subjects were determined to be healthy via physician-supervised medical history, examination, and routine blood and urine tests.

Pretest Measures

Prior to the 45-hour exercise, subject descriptive characteristics and baseline measures were obtained over a 5-day period. Height was measured with an anthropometer and mass with a calibrated digital scale. Body composition was estimated from neck and abdominal circumference (Vogel, Kirkpatrick, Fitzgerald, et al., 1988).

Subjects performed a progressive, interrupted load peak $\dot{V}O_2$ test for howitzer loading to establish a regression equation to predict oxygen uptake from heart rate during a loading exercise. The test involved four 5-minute exercise bouts in which 45-kg projectiles, or rounds, were lifted to waist height and loaded. Exercise intensity was increased by increasing the firing rate, which was 1.2, 1.4, 1.8, and 2.2 rounds per minute for bouts one through four, respectively. Successive exercise bouts were not conducted until the heart rate was at or below 100 beats/min^{-1}. To ensure maintenance of the loading rate, test administrators provided completion times for each round. During the activity, expired air was directed through a mouthpiece, into a low-resistance Hans-Rudolf valve and into an on-line gas analysis system. Oxygen concentration was determined with an Applied Electrochemistry S-3A gas analyzer; carbon dioxide concentration was determined with a Beckman LB-2 analyzer. Volumes were measured with an in-line KL Engineering Company turbine (Sylmar, CA). Heart rate was recorded continuously and averaged over 15-second intervals with a UNIQ heartwatch system (Polar Electronics, Finland).

Isometric hand-grip strength of the right hand was measured in a seated position using an adjustable grip device attached to a BLH load cell (BLH Electronics, Waltham, MA) and a Hewlett Packard computer (Teves, Wright, and Vogel, 1985). Subjects were instructed to build up to maximum tension over a 2-second period. If the initial buildup was not smooth, the trial was repeated. A mean of the best two trials within 10% of each other was selected as the final score. Lifting strength was measured on a weight-stack machine (Teves, Wright, and Vogel, 1985). Using a head-up, straight-back technique, subjects lifted handles attached to a weight stack from 30–152 cm above the floor. The initial load was 18.2 kg. Additional weight was added with each attempt, in increments of 4.5 kg, until the subject was unable to complete the lift. The last weight successfully lifted was the final score.

A profile of mood states (POMS) questionnaire and a rating of pain, soreness, and discomfort (RPSD) questionnaire were completed daily over the 5-day preexercise period (McNair, Larr, and Droppleman, 1981; Knapik, Staab, Bahrke, et al., 1991). The POMS is a 65-item questionnaire that provides measures of six mood states (tension, depression, anger, vigor, fatigue, and depression). Subjects score each question on a five-point scale from 0 (not at all) to 4 (extremely). The RPSD questionnaire requires subjects to rate their

level of pain, soreness, and discomfort for the front and back of 11 body sections on a scale of 0 (none) to 5 (extreme).

Simulator Exercise

The simulator exercise was 45 hours in length. It involved moving 45-kg artillery rounds from a supply vehicle to the field-artillery simulator and lifting, loading, and firing these rounds from the simulator. During the 45-hour exercise, subjects completed six cycles, each lasting 7.5 hours. There were five stations within each cycle, lasting 1.5 hours each. During each 1.5-hour period, field-artillery tasks were conducted for 75 minutes, and 15 minutes were allowed for rest, rotation of subjects, and administration of poststation testing.

Figure 1 illustrates one cycle. At Station 1 the subject in the resupply vehicle loaded rounds onto a conveyor belt and manually cranked the conveyor to move the rounds into the howitzer simulator. At Station 2 the subject was positioned next to the conveyor belt, which ran between the gun and resupply vehicle. The subject dislodged jammed rounds as they occurred to ensure a smooth flow of ammunition into the simulator. Inside the howitzer simulator, at Station 3, the subject loaded and fired the gun (the movements used to fire the gun are illustrated in Figure 2). During the last 15 minutes of Station 3, subjects completed the poststation testing. Stations 4 and 5 were consecutive inactive stations. A quiet area with cots was available for subjects to sleep and rest if they chose.

Forty rounds were fired in each 75-minute period. Rounds were fired in groups, called missions, of one or two, with one eight-round mission at the end of the period. The order and timing of missions varied, so they could not be anticipated. Mission time (a measure of howitzer loading performance) was calculated as the elapsed time between the order to fire rounds and the completion of the mission, summed over missions.

Heart rate was monitored continuously while the subject was inside the simulator at Station 3. Results were used to estimate energy cost from the individual heart rate to $\dot{V}O_2$ relationship established during the peak $\dot{V}O_2$ test. To validate the regression equations, oxygen uptake was mea-

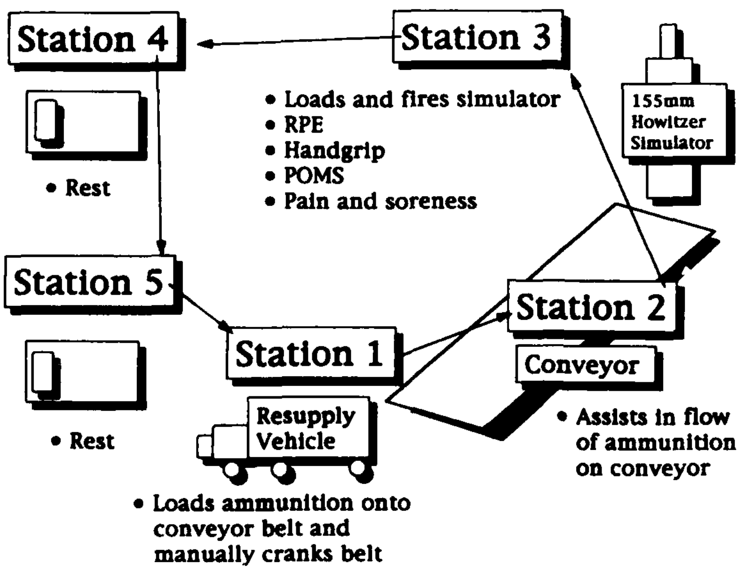

Figure 1. Personnel Rotation Diagram. Stations 1-5 were 90 minutes each, a full cycle (all five stations) was 7.5 hours.

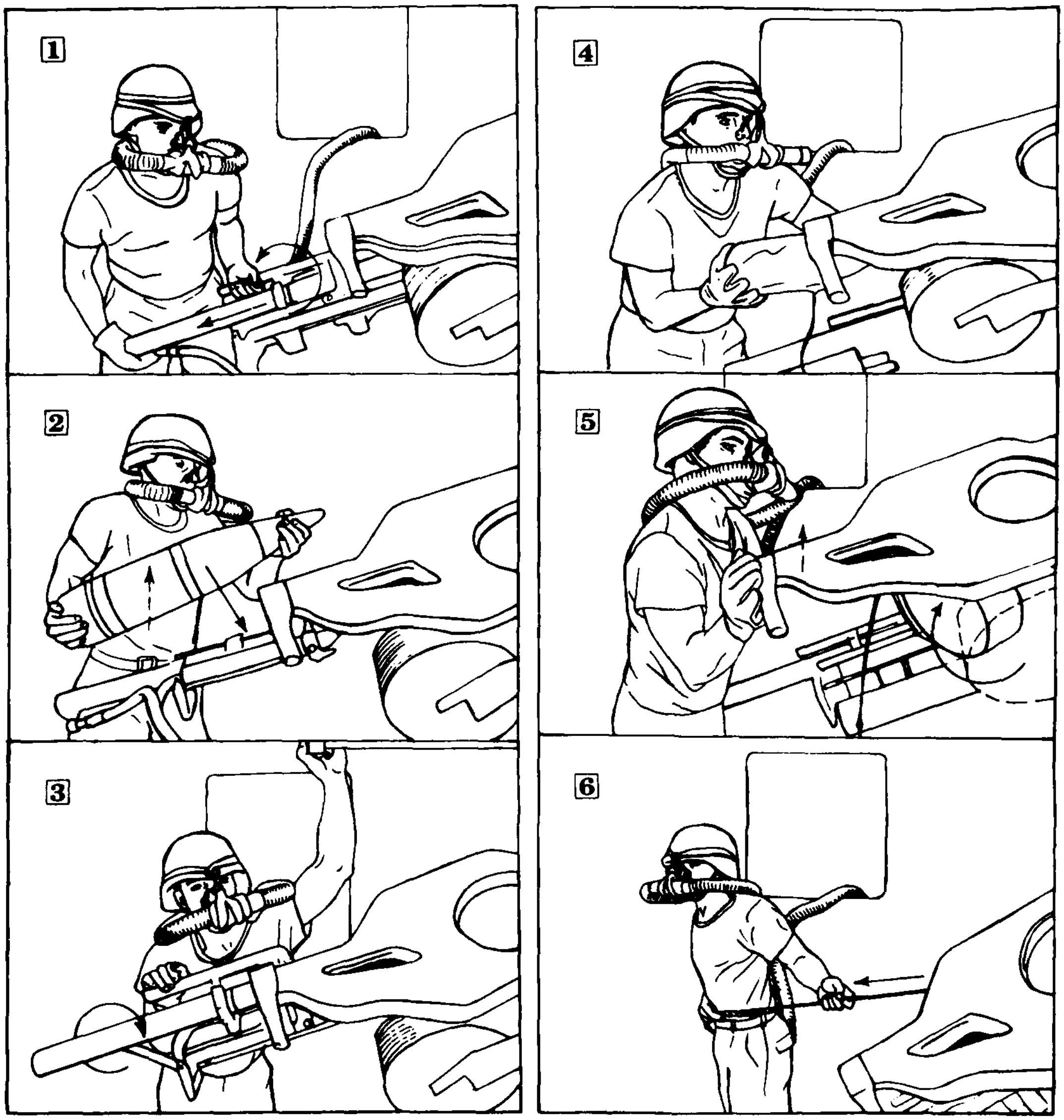

Figure 2. The Loading and Firing Process. *1*) The loading tray is lifted and locked into place. *2*) The round is lifted onto the tray and manually pushed into the barrel. *3*) The round is hydraulically forced into the barrel rifling. *4*) The loading tray is removed and a gunpowder bag is inserted into the barrel. *5*) The release handle is lifted and the breech slams shut. *6*) The lanyard is pulled to fire the gun.

sured as described above at two specific points at Station 3. The measurements were made at minute 30, during a series of four two-round missions ordered at 2-minute intervals, and during the final eight-round mission. Upon exiting the simulator at Station 3, subjects reported their ratings of perceived exertion (RPEs) for the upper body, lower body, and overall (Bailey, 1983), performed an isometric hand-grip test, and completed the POMS and RPSD questionnaires.

Statistical Analysis

All values for pretest measures were averaged to produce a single baseline measure. Repeated measures analysis of variance was used to assess changes during the simulator exercise. Tukey's HSD was used to isolate differences among the cycles.

RESULTS

The age, height, weight, percent body fat, lifting strength, and hand-grip strength of the nine crewmen were as follows (mean ± SD): 20.5 ± 2.3 years, 178.0 ± 9.5 cm, 81.6 ± 14.3 kg, 18.2 ± 6.7%, 89.9 ± 17.0 kg, 574.3 ± 112.2 N. The peak oxygen uptake (mean ± SD) for howitzer loading was 16.8 ± 3.1 kcal/min^{-1} (3.42 ± 0.67/min^{-1}). The ventilation and heart rate at peak $\dot{V}O_2$ was 102.5 ± 19.7/min^{-1}, and 187.8 ± 12.3 beats/min^{-1}, respectively.

A series of paired t-tests of the actual and predicted $\dot{V}O_2$ during the four two-round missions and the eight-round mission revealed no significant differences. Figure 3 shows the relationship between actual and predicted $\dot{V}O_2$ for the four two-round missions and the eight-round mission.

The predicted energy cost, mission time, and relative exercise intensity for each cycle are listed in Table 1. Predicted energy cost, mission time, and relative exercise intensity decreased as the exercise progressed ($p < 0.01$).

Tables 2 and 3 show the average values from each cycle for the measures taken at the end of Station 3. RPEs were higher in Cycle 6 than in the first few cycles ($p < 0.05$). Hand-grip strength was lower at the end of Cycle 6 compared to Cycle 1 ($p < 0.05$).

As illustrated in Figure 4, there were increases in tension and fatigue and a decrease in vigor ($p < 0.05$) as the exercise progressed, based on the POMS questionnaire. Figure 5 shows the areas where subjects reported significantly ($p < 0.05$) higher pain, soreness, and discomfort as the exercise progressed. RPSD increased 47% for the front and 77% for the back of the shoulders. 92% for the front and 85% for the back of the upper arms, 170% for the front and 100% for the back of the forearms, and 145% for the palm of the hand. There were no significant increases in the

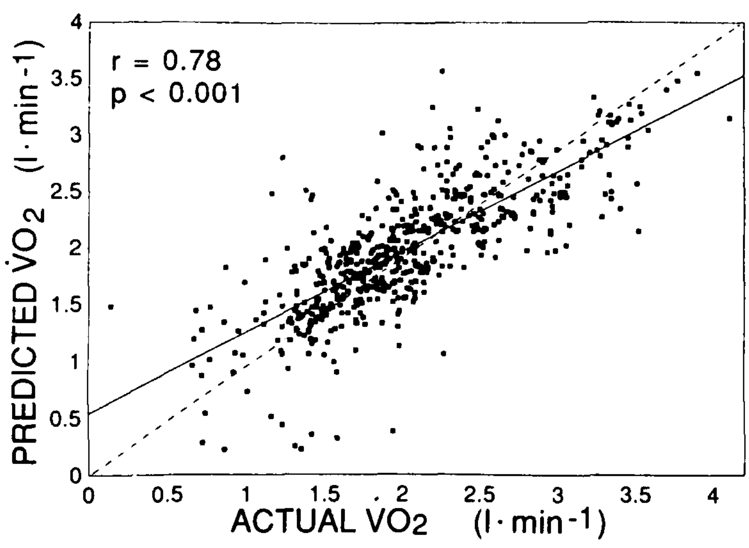

Figure 3. Scatterplot of Actual Versus Predicted $\dot{V}O_2$ Collected From Nine Subjects During the Four Two-round Missions and the Eight-round Mission.

Table 1. Predicted Energy Cost, Mission Time, and Relative Exercise Intensity During the Six Cycles at Station 3 (Mean ± SD)

Cycle	Energy Cost ($kcal/min^{-1}$)	Mission Time (min)	Exercise Intensity (% Peak $\dot{V}O_2$)
1	8.0 ± 1.3	28.1 ± 1.6	48.5 ± 8.4
2	7.0 ± 1.6	25.7 ± 2.1	41.9 ± 6.7
3	7.1 ± 1.6	24.3 ± 3.4*	43.0 ± 7.7
4	6.9 ± 1.7	24.5 ± 1.9*	41.8 ± 9.3
5	6.0 ± 2.0*	24.3 ± 3.0*	35.8 ± 9.3*
6	6.2 ± 2.1*	24.3 ± 3.3*	37.1 ± 13.2*

* Significantly different than Cycle 1 ($p < 0.01$).

lower back or legs, as might be expected with lifting exercises.

Preexercise measures of height, weight, body composition, strength, and peak $\dot{V}O_2$ were correlated with total energy cost, eight-round time, and mission time averaged over the six cycles. Subjects with a higher total energy cost had higher peak $\dot{V}O_2$ for howitzer loading ($r = 0.69$, $p < 0.05$), greater lifting strength ($r = 0.71$, $p < 0.05$), and greater hand-grip strength ($r = 0.71$, $p < 0.05$). Subjects with greater lifting strength had faster eight-round times ($r = -0.76$, $p < 0.05$). No other variables were significantly correlated.

DISCUSSION

This study demonstrated that exercise heart rate could be used to accurately predict the energy cost of an intense combined manual materials-handling task, based on a previously defined heart rate to $\dot{V}O_2$ relationship. The energy cost of howitzer loading has not been previously reported. Energy cost is dependent on the exercise intensity, which in this case is determined by the firing rate. The present study used a rate of 640 rounds/day, which is the highest rate envisioned in combat operations (U.S. Field Artillery School, unpublished observation, 1984). This rate resulted in a relative exercise intensity of 49% peak $\dot{V}O_2$ for howitzer loading in Cycle 1, which decreased to 37% of task-specific peak $\dot{V}O_2$ in Cycle 6. The National Institute for Occupational Safety and Health (1981) recommends an exercise intensity no greater than 33% $\dot{V}O_2$ max for an 8-hour workday, however, subjects did not work at this intensity for 8 hours continuously. They were intermittently active about 15 hours every 24 hours, with only about 4 hours per day involving loading activity at Station 3. The energy cost of Stations 1 and 2 was not measured, so it is not possible to determine how these stations contributed to the overall energy expenditure.

Table 2. RPEs Following Station 3 for Each Cycle (Mean ± SD)

Cycle	Upper Body	Lower Body	Overall
1	4.5 ± 2.1	3.9 ± 2.5	4.4 ± 2.1
2	4.2 ± 1.7	2.9 ± 2.0	4.4 ± 2.1
3	4.4 ± 1.3	3.2 ± 1.8	4.7 ± 2.1
4	4.6 ± 1.3	3.9 ± 1.9	5.0 ± 2.0
5	5.4 ± 1.7	4.1 ± 2.0	5.5 ± 1.7
6	5.7 ± 1.5*	4.6 ± 2.2†	5.9 ± 2.2‡

* Significantly different than Cycles 1, 2, and 3 ($p < 0.05$).
† Significantly different from Cycle 2 ($p < 0.05$).
‡ Significantly different from Cycles 1 and 2 ($p < 0.05$).

An important finding of the present study was the increase in metabolic efficiency and loading performance during the 45-hour exercise, as evidenced by a 23% decrease in energy cost and a 14% improvement in mission time. The improvement in mission time occurred rapidly, by the third cycle, while the metabolic improvement continued through the fifth cycle. The overall energy cost, or the product of the energy cost ($kcal/min^{-1}$ and mission time, decreased from 224.8 kcal during Cycle 1 to 150.7 kcal during Cycle 6. This decrease in energy cost represents an increase in efficiency of 33%, despite the fact that the subjects

Table 3. Isometric Hand-Grip Strength (N) Baseline and Following Station 3 for Each Cycle

		Cycle					
	Baseline	1	2	3	4	5	6
Mean	592.0	607.1	568.4	556.1	558.5	558.4	547.0*
SD	105.8	129.1	142.8	120.4	114.1	123.9	114.9

* Significantly different than Cycle 1 ($p < 0.05$).

were experienced field-artillery crewmen. During routine military training, soldiers seldom train with actual artillery rounds, particularly at such high rates of fire, because of the high cost, which may account somewhat for the improved efficiency. Improved efficiency may also be partially attributed to a reduction in accessory movements, which may have occurred with practice.

Despite the increased efficiency, there were indications of a decrement in physical capacity, and subjects perceived the exercise as being more difficult over time. Hand-grip strength declined and subjects reported higher levels of pain, soreness, and discomfort in the hands, arms, and shoulders. Subjects reported progressively increasing fatigue, tension, and perceived exertion in consonance with a past study of a field-artillery exercise (Krapik, Patton, Ginsberg, et al., 1987). These findings suggest that had the exercise continued, decrements in loading performance may have occurred.

The RPE reported following performance at Station 3 increased significantly during the course of the simulator exercise. Subjects perceived the exercise to be more difficult while actually expending less energy. Several studies have reported that RPE increases with repeated bouts of exercise, although the physiological responses to exercise have not changed (Martin and Gaddis, 1981; Ryman, Naitoh, and Englund, 1987). These authors suggest the RPE may be more related to psychological measures (e.g., fatigue, vigor, sleep-

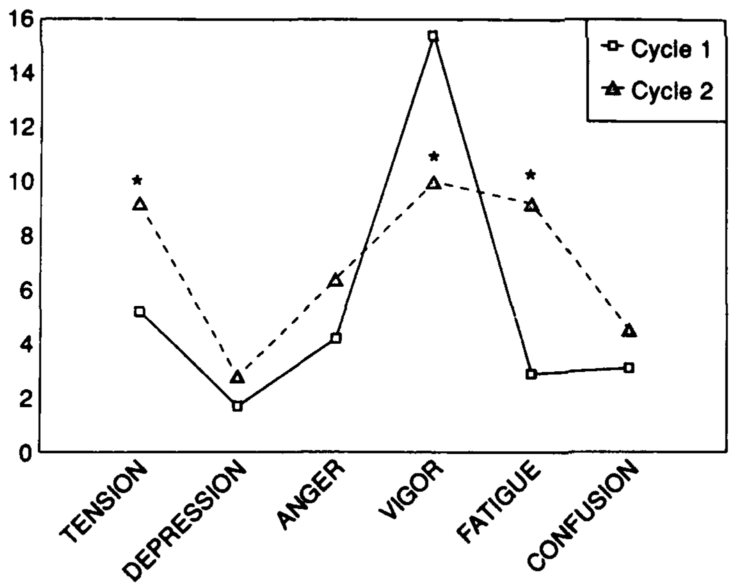

Figure 4. POMS following Cycles 1 and 6. *, Represents significant difference ($p < 0.05$) from Cycle 1 to Cycle 6.

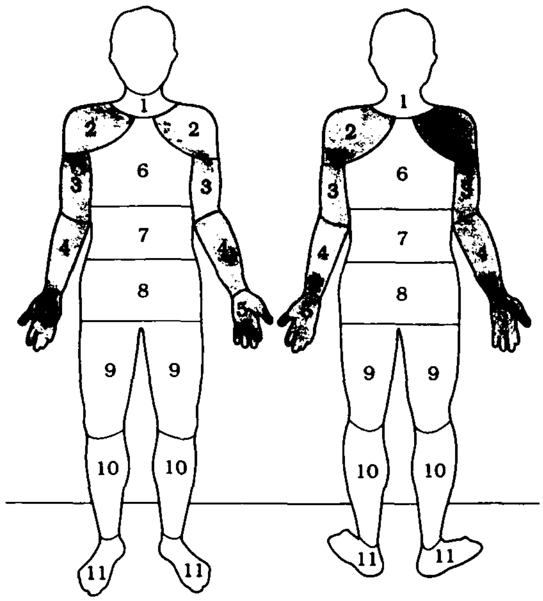

Figure 5. Body Diagram Used for RPSD. Areas where values increased significantly ($p < 0.05$) during the simulator exercise are shaded.

lessness) when repeated bouts of exercise are performed.

Subjects in the present study had higher average lifting strength than previously reported (Teves, Wright, and Vogel, 1985; Patton, Vogel, Damokosh, et al., 1989). Lifting strength was significantly correlated with eight-round mission time ($r = -0.76$), therefore, subjects with greater strength were able to complete the eight-round mission faster. Lifting strength appears to be an important factor in rapid loading and firing of the howitzer and should be considered when developing training programs for this occupation. It has been shown that lifting performance can be improved with strength training (Genaidy, 1991; Sharp, Harman, Boutilier, et al., 1993).

This data supports the use of simulators for training personnel to perform physically demanding tasks using machinery that is both dangerous and expensive to operate. Occupational training should be as realistic as possible (Bailey, 1983). It has been demonstrated in the literature that practice of a task can extend the limits of task performance, both in terms of task intensity and task endurance (Sharp and Legg, 1988; Genaidy, 1991; Genaidy, Gupta, and Alshedi, 1990). The use of a simulator allows for realistic training in a cost-effective manner. With the high cost of firing live ammunition, it would be extremely expensive to provide this type of experience to soldiers using a real gun. The intensity of exercise used in this study is seldom performed during peacetime training exercises. Participation in a short, high rate of fire exercise in a simulator improved speed of loading performance, as evidenced by a shorter mission completion time.

This study demonstrated that a trained field-artillery crew was able to maintain, and even improve, howitzer loading performance for a 45-hour period. Loading exercise became more metabolically efficient, and the work was completed in a shorter amount of time at the end of the 45-hour exercise. Individual perception of effort was increased, as were reports of pain, soreness, and discomfort, while muscle strength was decreased. These latter findings suggest that longer exercises (>45 hours) of a similar intensity may have fatiguing effects that could significantly impact on the performance of field-artillery soldiers.

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